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AEROSOL SAMPLING INLETS AND INHALABLE PARTICLES

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Abstract—The problem of sampling aerosols from the ambient atmosphere has been considered from a theoretical point of view. Following a review of the various samplers and inlets used in ambient sampling, the factors contributing to high sampling efficiency for large particles are discussed. It is pointed out that the major mechanisms for particle loss in sampling inlets are impaction on external surfaces, and impaction, turbulent deposition, and sedimentation on internal surfaces. Therefore, an efficient inlet is one for which these losses are minimized.

Based on these theoretical considerations, a new inlet for sampling inhalable particles (particles with aerodynamic diameter of 15 μm or less) has been designed, constructed and tested. The external geometry of the inlet has been selected to allow the efficient entry of large particles into the inlet opening. An impactor is then used to remove the coarse, non-inhalable particles. The inlet has been found to have essentially wind speed independent characteristics for wind speeds of up to 9 km h^{-1}, the maximum wind speed used in the tests. The impactor used has also been found to have sharp cut-off characteristics with a sharpness of cut parameter, σ_g, of 1.18.

INTRODUCTION

Sampling of aerosols from the ambient atmosphere is an important and necessary first step in atmospheric aerosol measurement. To obtain accurate measurement results, a representative aerosol sample must be drawn through an inlet into the particle measuring or collecting device. The sampling inlet is an important part of any aerosol measuring system and, as such, must be designed with care. An ideal inlet should allow all particles of interest to enter and arrive at the sensing or collecting zone of the instrument while excluding rain, snow, insects, plant matter, and other airborne debris. The performance of the inlet should also be unaffected by wind up to some maximum speed.

Inhalable particulate matter (IPM) has been defined by the Environmental Protection Agency (Miller *et al.*, 1979) as particles with aerodynamic diameters of 15 μm or less. New particulate air quality standards based upon IPM are being developed by the Agency. Unlike the conventional high-volume sampler which measures the total suspended particulates (TSP) with an uncertain cut-off size for large particles, samplers for IPM must have well-defined large particle cut size characteristics. The development of an inlet of high efficiency for particles of up to 15 μm aerodynamic diameter, therefore, is essential for the development of new IPM standards.

In this paper, we will first briefly review the various approaches to ambient aerosol sampling, with particular emphasis on inlet designs. A new inlet for the accurate sampling of IPM will then be described, together with the criteria of design and the performance data obtained on this new inlet.

AMBIENT AEROSOL SAMPLING AND INLET DESIGNS

A principal requirement of ambient aerosol sampling is that the instrument must be protected from rain and snow. This can be accomplished by means of simple weather-proof housings or more elaborate inlet designs to achieve high inlet efficiency. The term "inlet efficiency" is used here for the total transmission efficiency of the inlet system, defined as the fraction of particles transmitted by the inlet from the ambient atmosphere to the sensing or collecting zone of the instrument. For an inlet of a specific design, the inlet efficiency is generally a function of particle size, wind speed, and sampling flow rate. High inlet efficiency can be achieved easily for small particles, viz. those with diameters < a few μm. However, for large particles, high inlet efficiency can be obtained only with careful design.

High-volume sampler

The high-volume, or hi-vol, sampler is widely used for sampling atmospheric aerosols. It is the standard reference method for measuring ambient TSP (total suspended particulate) levels, in terms of which the national ambient particulate air quality standards are defined (Federal Register, 1971). In the standard hi-vol, a 20.3 cm × 25.4 cm (8″ × 10″) filter is placed horizontally within the main sampler housing, which is about 29 cm × 36 cm ($11\frac{1}{2}$″ × 14″) in cross-section. The clearance area between the main housing and the roof at its closest point is specified to be 580.5 ± 193.5 cm^2 (90 ± 30 in^2). Recent wind tunnel tests of the hi-vol by McFarland *et al.* (1979) showed that the D_{50} cut size

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16. ABSTRACT

The problem of sampling aerosols from the ambient atmosphere has been considered from a theoretical point of view. Following a review of the various samplers and inlets used in ambient sampling, the factors contributing to high sampling efficiency for large particles are discussed. It is pointed out that the major mechanisms for particle loss in sampling inlets are impaction on external surfaces and impaction, turbulent deposition, and sedimentation on internal surfaces. Therefore, an efficient inlet is one for which these losses are minimized.

Based on these theoretical considerations, a new inlet for sampling inhalable particles (particles with aerodynamic diameter of 15 μm or less) has been designed, constructed, and tested. The inlet incorporates an inlet configuration allowing for the efficient entry of large particles into the inlet opening, followed by an impactor to remove the coarse, non-inhalable particles. The inlet has been found to have essentially wind speed independent characteristics for wind speeds of up to 9 km/hr, the maximum wind speed used in the tests. The impactor has also been found to have sharp cut-off characteristics with a sharpness of cut parameter, σ_g, of 1.18. It is believed that this particular inlet will meet the requirements of a high efficiency inlet for sampling inhalable particles from the ambient atmosphere.

17. KEY WORDS AND DOCUMENT ANALYSIS

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(aerodynamic diameter corresponding to an inlet efficiency of 50%) is $> 30\ \mu m$ at a wind speed of 2 km h^{-1}, decreasing to about 30 μm at 8 km h^{-1} and 17 μm at 24 km h^{-1}. In addition, the inlet efficiency was found to depend on wind direction. Table 1 compares of the inlet efficiency of the hi-vol with several other ambient aerosol samplers and inlets.

Isokinetic sampling

In principle, isokinetic sampling can be used for atmospheric sampling. Although capable of high accuracy, isokinetic sampling is seldom used because the system to achieve true isokinetic conditions in the ambient atmosphere is necessarily complicated: the inlet must be directed to face the wind and the suction speed in the inlet must also be adjusted to match the wind speed. The latter task is extremely difficult to achieve under variable wind conditions.

In the "rotating-cowl" sampler (Fig. 1) developed by Sehmel (1973), a wind vane was used to direct the inlet of a 566.0 ℓ min^{-1} (20 cfm) cascade impactor against the wind. The suction speed in the inlet was kept fixed at 1.9 km h^{-1}. Thus, the sampler operated sub-isokinetically most of the time, except near calm air conditions. The sampler was used to collect particles up to 63 μm in diameter in the study of the resuspension of soil particles by wind. Tests by Wedding *et al.* (1977) at windspeed of 5.5 km h^{-1} showed that the inlet efficiency exceeded 82% for particles up to 15 μm in diameter.

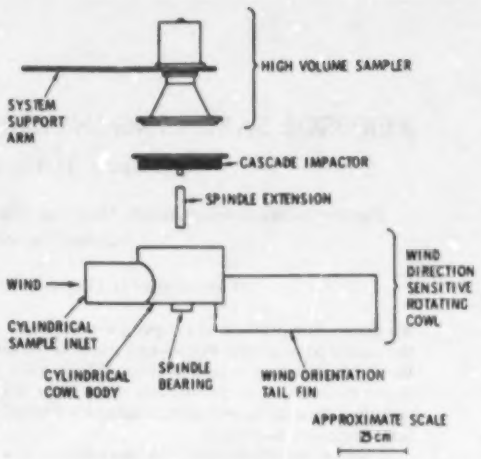

Fig. 1. The "rotating-cowl" sampler described by Sehmel (1973).

Inverted inlet

An inverted inlet may consist of a simple open-face filter operating face down, as shown in Fig. 2(a), or an open-face filter attached to a cylindrical tube, as shown in Fig. 2(b). Figure 3 shows an inverted inlet designed and tested by SRI (Southern Research Institute) (Bird *et al.*, 1973). The inlet efficiencies were found to be 39, 30 and 20%, respectively, for 5 μm diameter particles at wind speeds of 9.2, 46 and 68 km h^{-1}. For 12 μm

Table 1. Characteristics of ambient aerosol samplers and inlets

Sampler or inlet	Reference	D_{50} or D (μm) [efficiency (%)]	Wind speed (km h^{-1})
Hi-vol	McFarland (1979)	> 30	2
		30	8
		17	24
Rotating-cowl	Sehmel (1973)		
	Wedding *et al.* (1977)	15[82]	5.5
Rockwell inlet	Willeke and McFeters (1975)	25	0
SRI inverted inlet	Bird *et al.* (1973)	5[39]	9.2
		5[30]	46
		5[20]	68
		12[35]	9.2
		12[12]	46
		12[35]	68
Beckman dichotomous sampler inlet	McFarland *et al.* (1979)	15.5	2
		13	8
		10.5	24
Sierra dichotomous sampler inlet	Wedding and John (1979)	11	0
		22	5
		15	15
		10	42
Prototype dichotomous sampler inlet	Dzubay *et al.* (1977)		
	Wedding *et al.* (1977)	17.5	5.5
		13.5	16.5

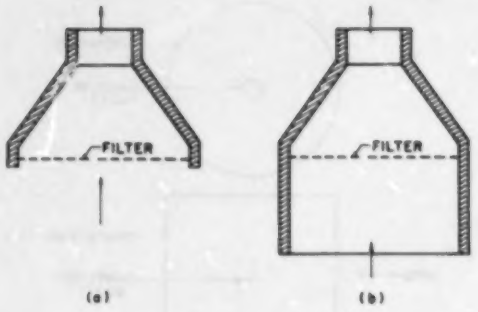

Fig. 2. The inverted inlet.

particles, the efficiencies were 35, 12 and 35%, respectively, at the same wind speeds.

Circumferential side-entrance inlet

Figure 4 is an omni-directional inlet of the circumferential side-entrance type. The inlet, designed and built by Rockwell International Corporation at the suggestion of the author (Liu) and his colleagues (K. T. Whitby and V. A. Marple), was used in EPA's CHAMP (Community Health Air Monitoring Program) stations for ambient air monitoring. The inlet incorporates a circumferential impactor to remove coarse particles. Tests by Willeke and McFeters (1975) showed that, at the sampling flow rate of 1133 ℓ min^{-1} (40 cfm), the cut-point of the circumferential impactor was 25 μm under calm air conditions. However, no data on the sampling efficiency as a function of wind speed are available.

Figure 5 shows another inlet of the circumferential, side-entrance type. The inlet, designed by McFarland *et al.* (1977), was intended for the virtual dichotomous sampler (Dzubay and Stevens, 1975). The same inlet design is now used in the commercial dichotomous samplers produced by Beckman Instruments, Inc. (Process Instrument Div., 2500 Harbour Blvd., Fullerton, CA 92634) and Sierra Instruments, Inc. (P.O. Box 909, Carmel Valley, CA 93924). Tests on the

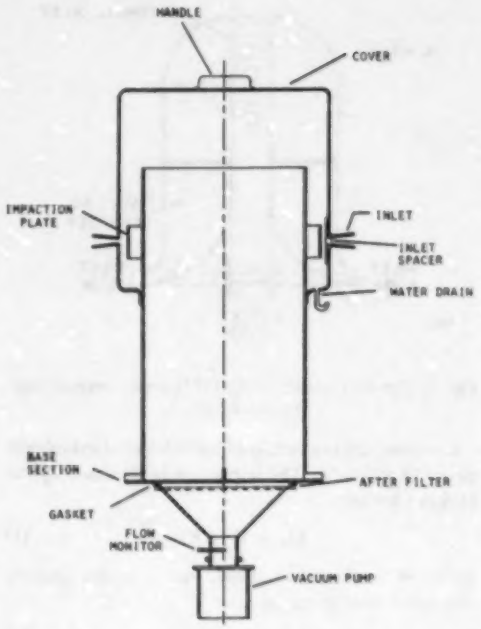

Fig. 4. The Rockwell circumferential side-entrance inlet.

Beckman inlet by McFarland *et al.* (1979) showed that the D_{50} size of the inlet was 15.5 μm at a wind speed of 2 km h^{-1}, decreasing to 13 and 10.5 μm, respectively, at wind speeds of 8 and 24 km h^{-1}. Similar tests by Wedding and John (1979) on the Sierra inlet resulted in D_{50} cut sizes of 11, 22, 15 and 10 μm, respectively, at wind speeds of 0, 5, 15 and 42 km h^{-1}.

Wind shield and baffles

The idea of using a wind shield or baffle to minimize the effect of wind on the inlet efficiency was suggested by the author (Liu) and more fully explored by Agarwal in a University of Minnesota Particle Technology Laboratory report (Agarwal, 1972).

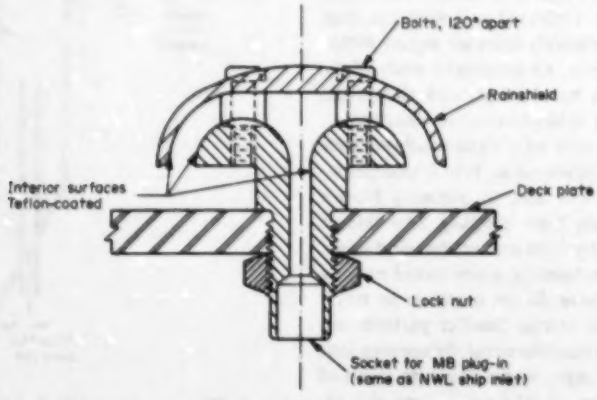

Fig. 3. The SRI inverted inlet.

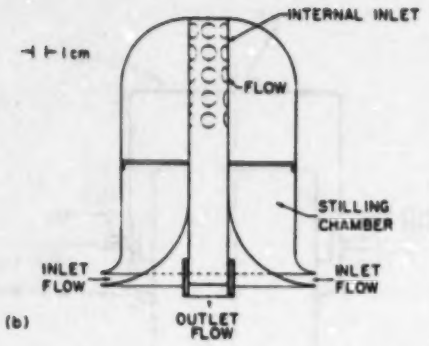

Fig. 5. The McFarland *et al.* (1977) circumferential side-entrance inlet.

Consider the impaction of particles on a cylindrical object of radius, R. The impaction is governed by the Stokes number:

$$St_w = W(\tau/R), \tag{1}$$

where W is the wind speed, and τ is the particle relaxation time given by

$$\tau = 2a^2 \rho_p C/9\mu \tag{2}$$

where a is the particle radius, ρ_p is the particle density, C is the slip correction, and μ is the gas viscosity. For impaction to occur, the Stokes number must be larger than some critical value. Thus, by choosing R to be sufficiently large, impaction can be prevented for particles of a certain size up to a certain maximum wind speed.

If particles are to be sampled into a tube of a radius, r, and the tube is placed at a right angle to the wind, particle impaction at the tube entrance will occur if r is small. However, if the tube is placed within a cylindrical wind shield or baffle of radius R, as shown in Fig. 6, and R is made sufficiently large, particle impaction on the wind shield can be prevented for particles of the same size at the same wind speed. If particle impaction does not occur on the wind shield, the aerosol concentration inside the wind shield must be the same as the concentration outside. Unbiased sampling can then take place from the relatively calm air region within the wind shield. However, no systematic study of the wind shield idea has been made, and the actual performance of the wind shield remains unknown.

Figure 7 shows the inlet of a virtual dichotomous sampler described by Dzubay *et al.* (1977) incorporating a wind shield. In this inlet, an auxiliary blower operating at a relatively high sampling flow rate of 200 ℓ min^{-1} draws in air from around the wind shield into the annular space, forming a downward-moving jet. Large particles above 20 μm continue to travel down because of their inertia. Smaller particles are drawn in through the circumferential slit opening into the vertical sampling pipe, where they are sampled isokinetically at a rate of 14 ℓ min^{-1} into the dichotomous sampler. This inlet was evaluated by

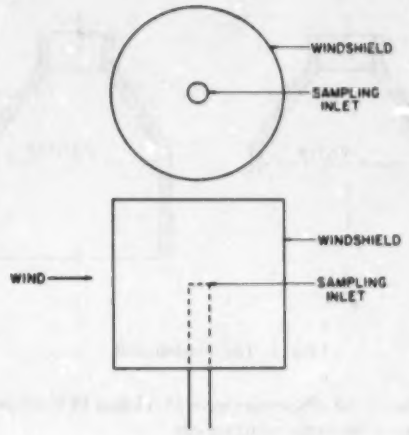

Fig. 6. Wind shield or baffle.

Wedding *et al.* (1977). The D_{50} size was found to be 13.5 and 17.5 μm at windspeeds of 5.5 and 16.5 km h^{-1}.

THEORETICAL CONSIDERATIONS

For an aerosol inlet to be efficient, particle loss must be small. Particle loss can occur on the external

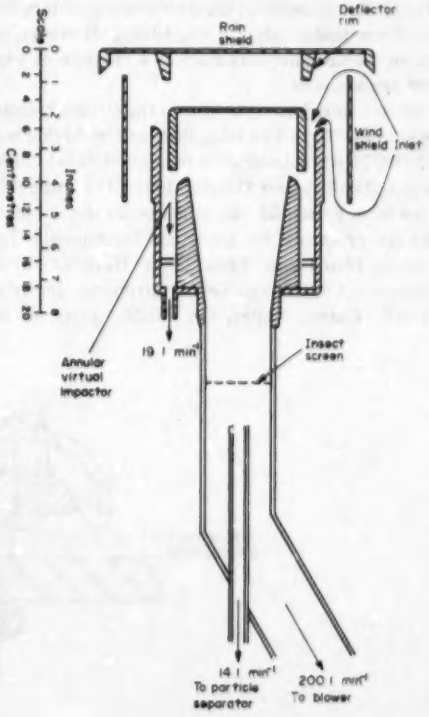

Fig. 7. The wind shield inlet for the virtual dichotomous sampler.

surfaces of an inlet or on internal surfaces. Therefore, an efficient inlet is one for which both the external and internal particle losses are minimized.

Consider, for instance, the circumferential, side-entrance inlet shown schematically in Fig. 8. With horizontal wind, particle impaction can occur on the external surfaces of the inlet because the streamlines entering the inlet are curved (curvature exaggerated to more clearly illustrate the effect), and the particle trajectories can deviate from the streamlines of the flow. This is depicted in the upper half of the figure. If the inlet is placed at a distance which is not too far from the instrument housing, streamlines deflected by the instrument housing can also enter the inlet at a rather sharp angle, causing additional impaction losses to occur. This is depicted in the lower half of the figure. Therefore, in designing aerosol inlets, both the external shape of the inlet, as well as the distance between the inlet and the main instrument housing, must be considered.

Once the particles are brought into an inlet by the streamlines, additional loss can occur by impaction, turbulent deposition, and sedimentation. Careful consideration of all three internal particle loss mechanisms must be made in order to arrive at a satisfactory design. Loss of particles by Brownian diffusion is generally unimportant in aerosol inlets because of the large particle size involved.

A completely rigorous theoretical approach to inlet design does not exist at the present time. Much of the previous theoretical work on aerosol inlets was concerned with sampling under calm air conditions (Davies, 1968; Kaslow and Emrich, 1973, 1974; Kim, 1974; Agarwal and Liu, 1980), and thus was not applicable to ambient sampling under wind. Similarly, the analysis of Davies (1976) and Davies and Subari (1978) on the sampling efficiency of a thin-walled tube in a cross-wind, while interesting in showing the mechanics of sampling, is not particularly useful in inlet designs, since the straight tube is known to perform poorly under moderate to high wind conditions and is thus not suitable as a general purpose high efficiency inlet. Thus, instrument designers, when faced with the problem of inlet design in the past, traditionally took a rather empirical approach, and many of the resulting inlets consequently have not performed too well.

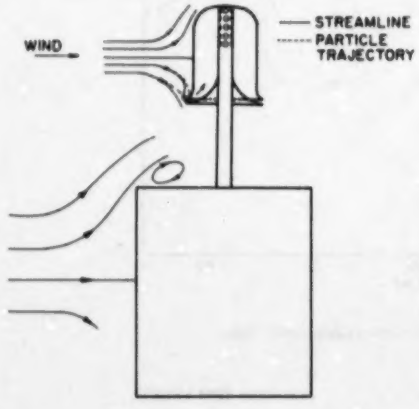

Fig. 8. Streamlines and particle trajectories around an aerosol inlet.

In the following discussions, we will show that it is not necessary to have a completely rigorous theoretical solution to the problem before an efficient inlet can be designed. We will show that, with a qualitative understanding of the fluid and particle mechanics involved, a satisfactory inlet can be designed.

Consider the three inlet configurations shown in Fig. 9. In Fig. 9(a), a simple vertical tube is used to sample the ambient aerosol into the instrument. With horizontal wind, particle impaction near the upstream side of the tube can occur because of the bending of the streamlines there. In Fig. 9(b), a circular flange is placed over the top of the vertical tube to deflect the streamlines which would otherwise enter the tube from below. The flange keeps the streamlines straight prior to their entry into the tube, thus eliminating particle loss by external impaction. Therefore, the design of Fig. 9(b) is inherently a more efficient design than that of Fig. 9(a). Similarly, in Fig. 9(c), the horizontal entrance near the top is enlarged compared to that in Fig. 9(b). This causes the streamlines to bend more gradually while entering the inlet, resulting in reduced impaction loss on the internal surfaces. Thus, of the three inlet designs shown in Fig. 9, the design of Fig. 9(c) should be the most efficient.

The inlet configuration of Fig. 9(b) and, by extension, that of Fig. 9(c), are similar to the case analyzed theoretically by Zebel (1978). Zebel showed that, for an inlet consisting of a slit in an infinite wall, the aspiration efficiency can be approximated by the equation:

$$E_1 = \frac{1}{1 + 1.09\mathrm{St}_w}, \tag{3}$$

where the aspiration efficiency is the ratio of the number of particles carried by the flow through the inlet opening to the number of particles in the original air volume in the ambient atmosphere, and St_w is the Stokes number based on wind velocity. In Zebel's (1978) calculation, potential flow was assumed. Figure 10 shows the streamlines near the entrance to the slit for the case where the wind speed, W, is equal to the suction speed in the slit. Zebel (1978) suggested that Equation (3) should also be applicable to the case of a circle hole in an infinite wall.

Figure 11 shows the performance of a sampling inlet predicted by Zebel's (1978) equation for a circular inlet of 9.2 cm ($3\frac{5}{8}$") diameter. The result shows that, for particles of 15 μm aerodynamic diameter, the aspiration efficiency is essentially 100% at low wind speeds, decreasing to 90% at a wind speed of 25 km h^{-1} and 80% at 57 km h^{-1}. Thus, Zebel's (1978) results suggest

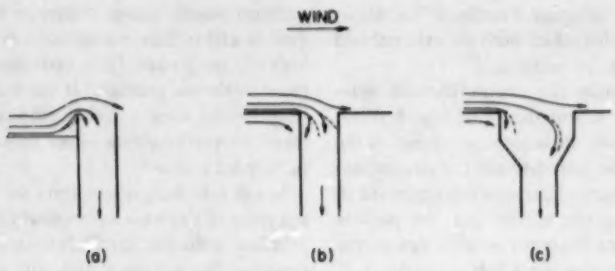

Fig. 9. Comparison of three aerosol inlets.

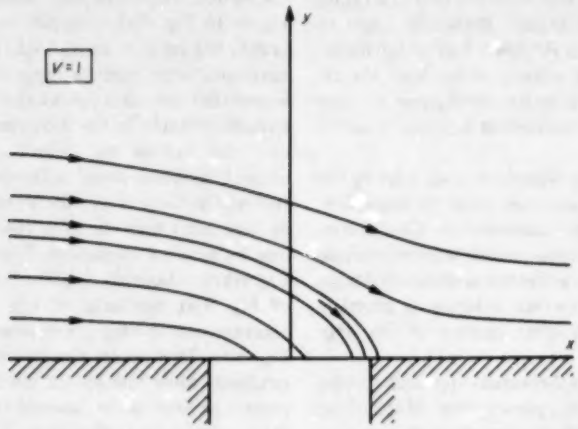

Fig. 10. Streamlines over a slit or hole inlet in an infinite wall.

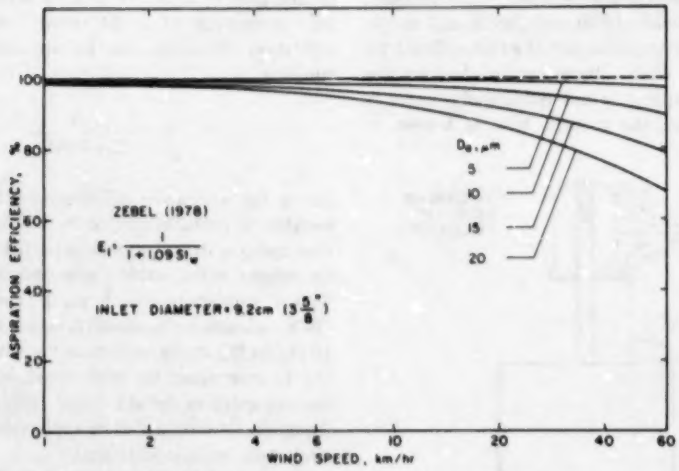

Fig. 11. Efficiency of the ideal "hole-in-an-infinite-wall" inlet.

that it should be possible to design an inlet to sample inhalable particles efficiently. The inlet performance can also be made reasonably independent of wind speed up to some rather high wind speeds.

A NEW IPM INLET

On the basis of the above considerations, we have designed the inlet shown in Fig. 12 for sampling

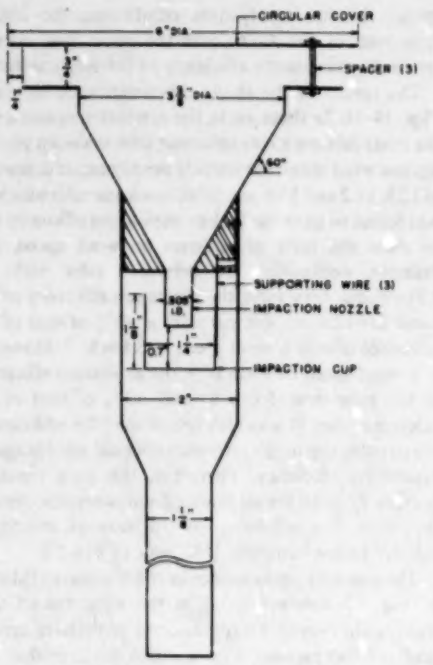

Fig. 12. The University of Minnesota aerosol inlet for inhalable particles.

inhalable particles. The specific inlet has been designed for the virtual dichotomous sampler, and for a sampling flow rate of $1\,m^3h^{-1}$ or $16.7\,\ell\,min^{-1}$. In addition to the several features described above, the inlet contains a circular top to keep out rain and snow, and an internal impactor to remove coarse particles above 15 μm. This inlet has been evaluated in the wind tunnel at various wind speeds up to 9 km h^{-1}, the maximum wind speed obtainable in our present wind tunnel. The experiments performed are described below, together with the data obtained.

DEFINITION OF TERMS

For purposes of describing the characteristics of the inlet shown in Fig. 12, the following efficiencies are defined:

E_1 = aspiration effeciency = m_1/m_0, (4)

E_2 = impactor transmission efficiency = m_2/m_1, (5)

E = total transmission efficiency of the inlet system, or the inlet efficiency = $m_2/m_0 = E_1E_2$, (6)

where:

m_1 = mass of particles carried by a given volume of flow through the exit plane of the impactor nozzle,

m_2 = mass of particles carried by the same volume of flow through the exit plane of the inlet system, and

m_0 = mass of particles in the same volume of air in the ambient atmosphere. All particle masses referred to above are for particles of a certain size.

The aspiration efficiency, E_1, defined previously, is similar to the aspiration coefficient defined by Davies (1968) or the suction coefficient defined by Zebel (1978) [Eq. (3)]. The only difference is that the aspiration efficiency is defined in terms of the particle mass passing through the exit plane of the impactor nozzle, whereas the aspiration or suction coefficient is usually defined in terms of the particle mass brought in by the flow through the inlet opening, in this case, the top of the funnel. Thus, the aspiration efficiency takes into account the particle loss in the entrance portion of the impactor nozzle, whereas the aspiration or suction coefficient does not. However, since particle loss in funnel portion of the inlet has been found to be small for particles in the inhalable size range, the difference between aspiration efficiency defined here and the aspiration or suction coefficient defined by Davies (1968) and Zebel (1978) is not large and, for all practical purposes, can be ignored.

The impactor transmission efficiency, E_2, defined by Equation (5), is usually referred to as "penetration" in impactor studies. However, in the present case, the impactor is used to remove the non-inhalable particles and to transmit the inhalable particles efficiently. The term "impactor transmission efficiency", therefore, appears appropriate. Finally, the total transmission efficiency of the inlet system, E, or the inlet efficiency for short, is the same as the "inlet effectiveness" defined by McFarland *et al.* (1977 and 1979). However, we prefer the term "efficiency" because in engineering usage, efficiency generally means, and is usually defined as, the ratio of the desired output to the input. For example, the efficiency of a power plant is defined as the ratio of the energy output of the power plant to the energy input. In the present case, the inlet system may be considered as a particle transmission device, the desired output being the aerosol transmitted or delivered to the sampling or measuring instrument, and the input, the aerosol drawn in from the ambient atmosphere. Therefore, the term "inlet transmission efficiency", or the "inlet efficiency" for short, is consistent with the general usage of the term efficiency.

EXPERIMENTAL STUDY AND RESULTS

The preliminary tests of the inlet completed were of two main types. In one type of test, the inlet was evaluated with an optical particle counter in the wind tunnel and its performance compared with several other inlet configurations. The purpose of these experiments was to compare the relative performance of the several inlet configurations in order to see if the chosen configuration indeed had the highest aspiration efficiency. For these experiments, the absolute value of the aspiration efficiency was not needed. In the second type of test, the absolute aspiration efficiency of the

inlet was measured, as well as the absolute impactor transmission efficiency and the absolute inlet efficiency. The measurement was made by sampling the particles through the inlet and through an isokinetic probe, and comparing the collected particle mass by fluorometric analysis.

The experiments were performed in the low-speed wind tunnel facility of the Particle Technology Laboratory. The wind tunnel has a 50 cm × 50 cm (20″ × 20″) test section and is capable of a maximum wind speed of 9 km h^{-1}. The projected area of the inlet in the direction of flow is about 125 cm^2. Thus, about 5% of the test section area was blocked by the inlet under test. A complete description of the wind tunnel facility has been given by Whitby *et al.* (1958).

Figure 13 shows the test setup for measuring the relative performance of the inlets by means of an optical particle counter (OPC). Monodisperse aerosols of oleic acid were generated by the vibrating orifice monodisperse aerosol generator (Berglund and Liu, 1973) and introduced into the wind tunnel. The particles were then sampled into an optical particle counter (Royco 245, Royco Instruments, Inc., 141 Jefferson Drive, Menlo Park, CA 94025) through the different test inlets. By comparing the counts registered by the OPC when different inlets were used, the relative performance of the inlets could be determined. For these experiments, the impactor was removed from the inlet shown in Fig. 12, and the entire flow of 16.7 ℓ min^{-1} passing through the inlet was sampled into the Royco 245 counter. The geometrical diameter of the particle was calculated from the liquid flow rate, the solution concentration, and the vibrating frequency in accordance with the method described by Berglund and Liu (1973). The geometrical diameter was then converted to aerodynamic diameter by multiplying by the factor $\sqrt{\rho_p}$, where $\rho_p = 0.894$ g cm^{-3} is the density of oleic acid.

The inlets tested included the UM inlet of Fig. 12 with the circular top and impactor cup removed—referred to here as the reference inlet—a funnel inlet (the UM inlet without the top, flange and impactor cup), and two tube inlets consisting of straight 5.08 cm (2″) and 3.81 cm (1½″) dia. tubes which were placed perpendicular to the horizontal wind in the wind tunnel. Under steady-state conditions, the counts registered by the OPC over the same time interval represent the relative efficiency of the inlets tested.

The results of the above experiments are shown in Figs. 14–16. In these plots, the aspiration efficiency of the inlets relative to the reference inlet is shown plotted against wind speed for particle aerodynamic diameters of 12.8, 14.2 and 15.6 μm. In all cases, the reference inlet was found to have the highest aspiration efficiency and to show the least dependence on wind speed. For example, comparing the reference inlet with the 3.81-cm dia. tube inlet, the aspiration efficiency of the latter for 12.8-μm dia. particles is 90% of that of the reference inlet at a wind speed of 3 km h^{-1}. However, at a wind speed of 9 km h^{-1}, the aspiration efficiency of the tube inlet drops to only 12% of that of the reference inlet. It was also found that the addition of the circular top to the reference inlet did not change its aspiration efficiency. Therefore, the data obtained previously were, for all practical purposes, the same as the aspiration efficiency of the various test inlets relative to the complete UM inlet of Fig. 12.

The absolute performance of the complete UM inlet of Fig. 12 was evaluated in the wind tunnel with fluorescein-tagged DOP (di-octyl phthalate) aerosol and by comparison with an isokinetic probe. The aerosol was generated by dissolving DOP and fluorescein in isopropyl alcohol and spraying the solution through the vibrating orifice droplet generator. The geometrical diameter of the aerosol was similarly calculated from the droplet generator operating conditions and converted to aerodynamic diameter by multiplying by $\sqrt{\rho_p}$, where $\rho_p = 0.980$ g cm^{-3} is the density of DOP. Since the amount of fluorescein used was small (about 2% of the DOP mass in most cases), the slight increase in droplet density due to fluorescein addition was ignored.

In these tests with fluorescein-tagged DOP aerosol, a Millipore filter was mounted directly at the exit of the UM inlet to sample the particles passing through the inlet. Following sampling, the fluorescein was extracted from the filter by immersing the filter in 20–80 ml of a 0.01 N aqueous solution of NaOH. The solution and filter were then agitated in an ultrasonic bath for 2–3 min. The fluorescein concentration in the

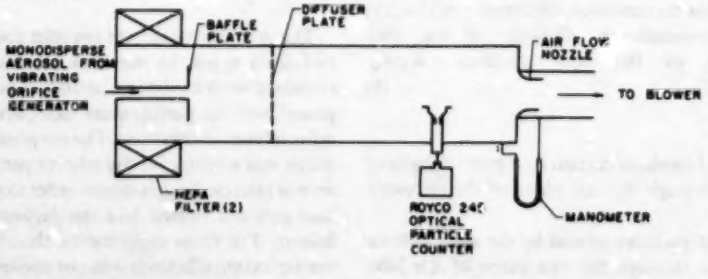

Fig. 13. Test set up for measuring the relative efficiency of different inlet configurations.

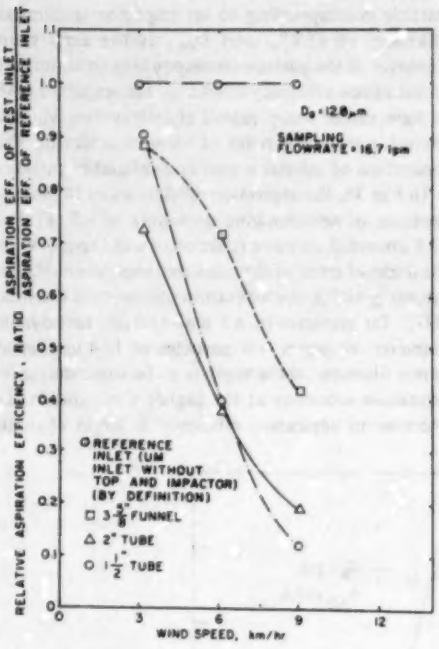
RELATIVE ASPIRATION EFFICIENCY, RATIO ASPIRATION EFF. OF TEST INLET / ASPIRATION EFF. OF REFERENCE INLET
D_a = 12.8 μm
SAMPLING FLOWRATE = 16.7 lpm
REFERENCE INLET (UM INLET WITHOUT TOP AND IMPACTOR) (BY DEFINITION)
3-5/8" FUNNEL
2" TUBE
1-1/2" TUBE
WIND SPEED, km/hr

Fig. 14. Relative performance of several inlet configurations for 12.8-μm dia. particles.

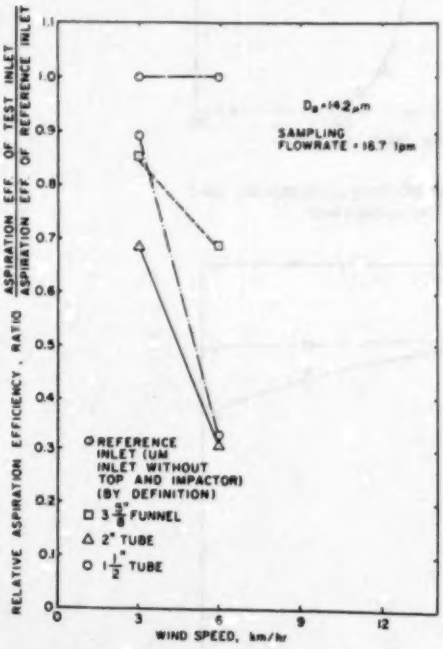
RELATIVE ASPIRATION EFFICIENCY, RATIO ASPIRATION EFF. OF TEST INLET / ASPIRATION EFF. OF REFERENCE INLET
D_a = 14.2 μm
SAMPLING FLOWRATE = 16.7 lpm
REFERENCE INLET (UM INLET WITHOUT TOP AND IMPACTOR) (BY DEFINITION)
3-5/8" FUNNEL
2" TUBE
1-1/2" TUBE
WIND SPEED, km/hr

Fig. 15. Relative performance of several inlet configurations for 14.2-μm dia. particles.

solution was then measured with a fluorometer (Model 110, G. K. Turner Associates, 2524 Pulgas Ave. Palo Alto, CA 94303, U.S.A.). The filter at the exit of the

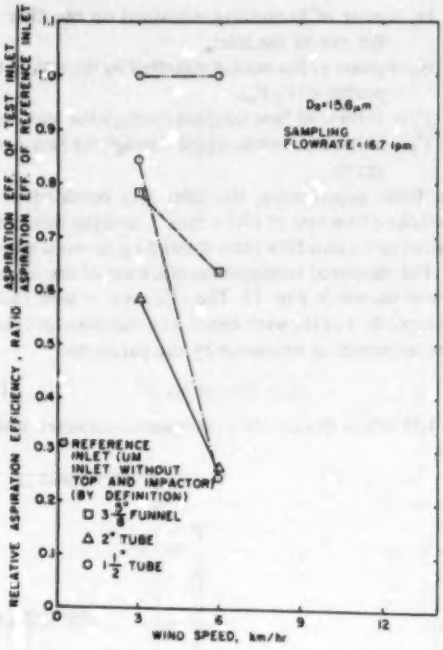
RELATIVE ASPIRATION EFFICIENCY, RATIO ASPIRATION EFF. OF TEST INLET / ASPIRATION EFF. OF REFERENCE INLET
D_a = 15.6 μm
SAMPLING FLOWRATE = 16.7 lpm
REFERENCE INLET (UM INLET WITHOUT TOP AND IMPACTOR) (BY DEFINITION)
3-5/8" FUNNEL
2" TUBE
1-1/2" TUBE
WIND SPEED, km/hr

Fig. 16. Relative performance of several inlet configurations for 15.6-μm dia. particles.

isokinetic probe was similarly analysed. To measure the material deposited on the inside surface of the isokinetic probe, a wet cotton swab was used to wipe the inside surface of the probe clean. The cotton swab was then immersed in 20 ml of wash solution and similarly agitated in an ultrasonic bath for 2–3 min. to extract the fluorescein from the cotton swab. Generally, very little material was found on the inside surface of the isokinetic probe.

To measure the material collected on the inside surface of the impaction cup, the outside surface was first wiped clean with a wet cotton swab and 20 ml of wash solution was added to the cup and ultrasonically agitated. The solution was then analysed. The same cotton swab was used to wipe the remaining surfaces in the inlet to determine the wall losses in the inlet. The cotton swab was then similarly analysed.

From these measurements, the various efficiencies were calculated as follows:

$$\text{Impactor transmission efficiency} = m_f/(m_i + m_w + m_f), \quad (7)$$

$$\text{Inlet aspiration efficiency} = (m_i + m_w + m_f)/m_0, \quad (8)$$

$$\text{Inlet transmission efficiency} = m_f/m_0, \quad (9)$$

$$\text{Wall loss} = m_w/(m_i + m_w + m_f), \quad (10)$$

where:

m_i = mass of fluorescein deposited on the impaction cup,

m_w = mass of fluorescein deposited on the remaining wall surfaces of the inlet downstream of the impactor nozzle,

m_f = mass of fluorescein deposited on the filter at the exit of the inlet,
m_0 = (mass of fluorescein collected by the isokinetic probe) × (V_i/V_0),
V_i = volume of flow sampled through the inlet, and
V_0 = volume of flow sampled through the isokinetic probe.

In these experiments, the inlet was operated at a sampling flow rate of 16.7 ℓ min^{-1}, and the isokinetic probe at various flow rates depending on wind speed.

The measured transmission efficiency of the impactor is shown in Fig. 17. The efficiency is seen to be independent of the wind speed. The sharpness of cut of the impactor, as measured by the parameter:

$$\sigma_g = (D_{15.9}/D_{84.1})^{\frac{1}{2}} \tag{11}$$

is 1.18 where $D_{15.9}$ is the aerodynamic diameter of the particle corresponding to an impactor transmission efficiency of 15.9%, and $D_{84.1}$ is the aerodynamic diameter of the particle corresponding to an impactor transmission efficiency of 84.1%. The impactor is seen to have rather sharp cut-off characteristics which are desirable from the point of view of achieving sharp separation of inhalable and non-inhalable particles.

In Fig. 18, the aspiration efficiencies of the inlet for particles of aerodynamic diameters of 8.5, 11.0 and 13.4 μm are shown as a function of wind speed. Within the limits of error of the measured aspiration efficiency (about ±10%), the aspiration efficiency is essentially 100% for particles of 8.5 and 11.0 μm aerodynamic diameter. However, for particles of 13.4 μm aerodynamic diameter, there appears to be some decrease in aspiration efficiency at the higher wind speeds. This decrease in aspiration efficiency is larger than that

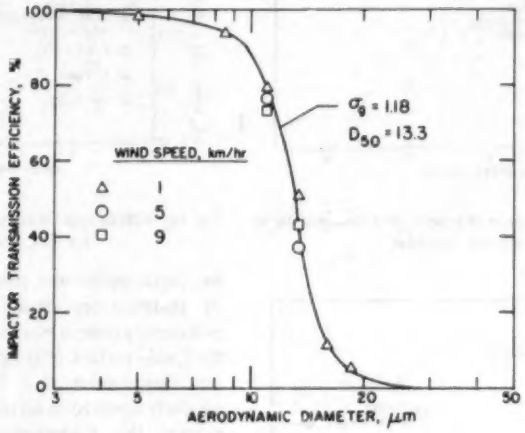

Fig. 17. Experimental transmission efficiency of the impactor used in the University of Minnesota inlet.

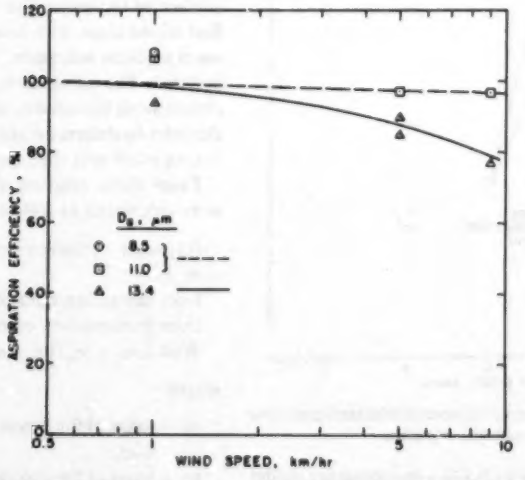

Fig. 18. Experimental aspiration efficiency of the University of Minnesota inlet.

predicted by Zebel's (1978) theoretical equation. This suggests that the flow field at the inlet is more complicated than that assumed by Zebel (1978) in his analysis.

In Fig. 19, the overall transmission efficiency of the inlet is shown. The change in inlet efficiency with wind speed is very slight and, for all practical purposes, negligible. Also shown for comparison are the characteristics of the inlet used in the Beckman dichotomous sampler (McFarland *et al.*, 1979).

The wall loss data for the present inlet are shown in Table 2. The maximum wall loss observed is 8.1% for particles of 11.0 μm aerodynamic diameter, and the average wall loss for all the tests combined is 1.85%.

Table 2. Wall loss in UM inlet

Wind speed (km h^{-1})	D_a (μm)	Wall loss (%)
1	5	0.9
	8.5	1.0
	11	8.1
	13.4	0
	16	0.1
	18.5	0.9
5	11	3.0
	13.4	0.4
9	11	3.8
	13.4	1.3

DISCUSSIONS, CONCLUSIONS AND FUTURE WORK

When using the inlet described above on an actual aerosol sampling instrument, the distance between the inlet and the instrument is important and must be considered. If the inlet is installed too close to the main instrument housing, the situation depicted in Fig. 8 could arise where the streamline deflected upward by the housing could interfere with the operation of the inlet, thereby degrading its performance. It is recommended that the distance between the inlet and the top of the main instrument housing be kept equal to or larger than the height of the instrument housing, as shown in Fig. 20(a). If it is not possible or desirable to have this minimum distance of separation between the inlet and the instrument housing, a horizontal deflection plate can be installed over the top of the instrument housing, as shown in Fig. 20(b), to prevent the streamlines deflected upward by the instrument housing from interfering with the inlet operation. With these precautions, it is believed that the performance of the inlet, as determined for an isolated inlet in a wind tunnel, should be the same as the actual performance of the inlet when installed on the instrument.

Based on the work performed so far, we believe the inlet described above will meet the basic requirement of an inlet for sampling inhalable particles from the ambient atmosphere. However, the D_{50} diameter of the present inlet is 13.3 μm, which is somewhat smaller than the 15.0-μm dia. that was intended. The D_{50} diameter can be increased by increasing the impactor nozzle diameter slightly, from the present value of 1.28 cm to 1.39 cm. This slight increase in nozzle

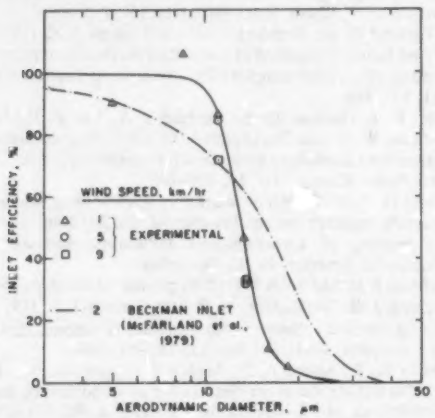

Fig. 19. Experimental inlet efficiency for the University of Minnesota inlet and its comparison with the Beckman dichotomous sampler inlet.

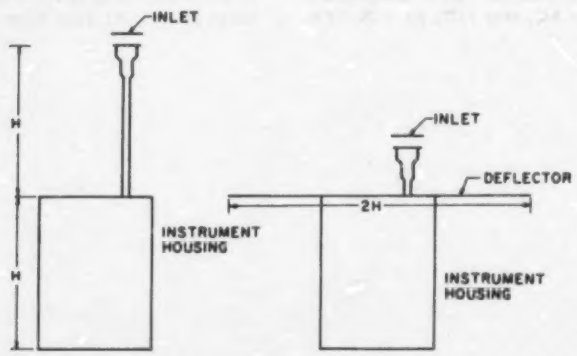

Fig. 20 Two methods of installing an inlet on an aerosol sampling instrument.

diameter should not affect the inlet operation in other respects.

Before the present inlet is adopted for routine sampling, it is desirable that additional tests be performed. In addition to wind tunnel testing at higher wind speeds, the inlet should also be tested for its actual field performance characteristics. Some limited tests have shown that the inlet is weather-proof, at least for rain, i.e. the circular top is effective in keeping out rain. We believe that insects, plant matter and other airborne debris would, by virtue of their large size, the effectively trapped by the impaction cup. By coating the inside surface of the impaction cup with a non-volatile grease, particle bounce and re-entrainment could also be prevented. However, actual tests with solid particles should be made to see if particle bounce and re-entrainment can indeed be prevented.

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